Planning for VLA/DSN Arrayed Support to the Voyager at Neptune

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Preplanning for the use of the National Radio Astronomy Observatory's Very Large Array (VLA) in support of Voyager at Neptune has been underway since early 1982. When arrayed with the DSN antennas at Goldstone, CA, the VLA more than doubles the potential data return over the American longitude for the 1989 Voyager encounter. This report summarizes the background, rationale, and current status of planning for VLA-DSN Arrayed Support to the Voyager at Neptune.

I. Introduction

The Very Large Array (VLA) is an array of twenty-seven 25-meter antennas in a triradial configuration in the high New Mexico desert. The primary role of this array is developing maps of radio-bright objects in the sky, and it incorporates a large mapping processor which is capable of cross-correlating the 351 (=27*26/2) baselines of the array in real time (Ref. 1). One of the optional products of this mapping processor is a combined output which represents the coherent sum of the signals being received at each of the antennas. This combined output of the mapping processor will represent about two and a half of the DSN's 64-meter apertures when all of the VLA antennas are outfitted with X-band low noise amplifiers.

A study of the possible use of the VLA for the support of the Voyager encounter of Neptune in August of 1989 was commissioned by an exchange of letters in early 1982 between Dr. B. C. Murray, then Director of the JPL, and Dr. M. S. Roberts, then Director of NRAO. The study was handled at JPL concurrent with the somewhat broader Interagency Array Study which considered the total complement of possible non-DSN receiving apertures that might be appropriate for support of the Voyager (Ref. 2). That study reported its conclusions in early 1983, with positive recommendations for the VLA and a few other observatories. Engineering studies have continued since that time, and are reflected in this article.

At the present time, Voyager is virtually unique in the benefits that can be derived by arraying. The reason becomes clear when one realizes that the Voyager was fundamentally designed to give the superb coverage it did at the Jupiter and Saturn encounters, but with a flight path which would much later take it past the far outer planets Uranus and Neptune (Ref. 3). Compensating for the increased distance is being done partially by changes to the on-board control software, but to provide outer planet coverage akin to that at

Saturn will require a substantial increment to ground receiving capability. Equipping a new mission for Voyager-style return at these far outer planets would take many years, and many hundreds of millions of dollars. The flight of the Voyager presents a once-in-a-lifetime opportunity for today's scientists and scientific institutions.

The main message from the study was this: Considering all aspects, including the timeliness and costs of building antenna facilities, and the scientific potential and uniqueness of the Voyager, it is appropriate that most of the additional aperture needed to support the Uranus and Neptune encounters be obtained by enlisting the help of the world's large receiving facilities, providing that such help could be mutually arranged. For the particular case of the VLA, configuring it to provide the equivalent of 2.5 times today's DSN 64-meter antenna capability would boost the receiving aperture over the American longitude so that coverage is available for both the best compressed imaging data rate, and for several of the alternative (higher) data rates without image data compression.

This article updates the VLA material from the Interagency Array Study Report which appeared in *TDA Progress Report 42-74* (Ref. 2).

II. Voyager Mission Characteristics

The objectives of the Voyager mission to Neptune are, generally, to extend the comparative studies of the outer planets to include the environment, atmosphere, surface and body characteristics of the planet Neptune; one or more of its satellites, with emphasis on Triton, and a search for rings. Typical specific scientific objectives to be addressed at Neptune include measurements of the gross morphological structures of the planet and satellites; determination of the Neptune atmospheric composition, structure, and dynamics; determination of the Neptune rotation period; detailed magnetospheric and plasma studies; a study of the satellite surface features, temperatures, and probable Triton atmosphere; and a study of the Neptune rings, if they exist.

The Voyager trajectories, from launch in 1977 onward, are shown in Fig. 1. As can be seen, the decline in Voyager signal strength from Jupiter to Uranus is some 10 dB due to the increase in distance, and the decline from Uranus to Neptune will be another 3.5 dB, most of which must be accommodated on the ground. Figure 2 shows the configuration of the DSN as we expect it to be in 1989, together with the more prominent of the world's apertures which were considered by the interagency array study. It should be noted that the DSN as pictured in this figure is not identical to the network as it will exist in 1986, but includes a performance upgrade of the present 64-meter antennas, and a new high-efficiency 34-meter antenna in Spain.

The telecommunications link performance of the Voyager spacecraft with the 1989 DSN and selected other apertures arrayed is shown in Fig. 3. The horizontal axis of this figure is indexed by GMT hours (Earth-received time) for the day of encounter in August, 1989. The time of closest approach to Neptune is at 08:06, and the time of closest approach to Triton, the largest satellite, is at 13:16 hours. The VLA is well positioned to return the final several hours of Neptune bright-side imaging, as well as to off-load the tape recorder to make room for Triton images. The left axis of this figure is labeled in terms dB of total received signal-to-noise ratio for a reference data rate of 1 bit/s, and the arcs of the figure indicate the effective (normalized) received signal strength. The cruves represent 90% confidence levels, and include the nominal weather statistics and availability of individual antennas. The right-hand axis is labeled to indicate the threshold levels applicable to various Voyager data rates. Communication is feasible at a given rate whenever the received signal strength exceeds the associated threshold level. The information content of the various rates is shown in Table 1. The higher of the two compressed imaging data rates is made feasible by the arraying with two apertures: Parkes Radio Telescope in Australia, and the VLA (2.5 equivalent 64-meter antennas) in the American longitude.

III. Arraying Configuration and Requirements

The functional block diagram for arraying between the DSN Goldstone site and the VLA is shown in Fig. 4. The X-band signal of the Voyager is received concurrently at the DSN facilities and by the observatory. The X-band receiver provides phase-coherent detection of the spacecraft signal, and emits a baseband version of it which contains the same data as the comparable signal at the DSN station. Functional requirements include the provision of a real-time link between the observatory and the DSN site, as well as local recorders at both sites. These would always record the signals, and could enable near-real-time arraying, but would primarily provide backup in case of difficulty with the real-time link. The combiner must be capable of operating with either the link or with the recorders.

With the configuration as shown, the choice is available to operate either using the link as the primary pathway, or with the recorded signal as the primary pathway. Using the real-time link is preferred from an operational standpoint because it provides immediate validation of the array operation, gives the flight project personnel immediate visibility into their data, and avoids the effort and cost of transporting and processing tapes, unless link outages occur.

Figure 5 shows the currently planned VLA configuration for Voyager support. The items to be added to the VLA include X-band feedhorns, low-noise amplifiers and down-converters at the front ends, and the phase-locked receiver and coherent detector at the combined output of the VLA processor. Use of the VLA's intrinsic signal transmission facility has the advantage that the spacecraft signal reception capability can be tested, and perhaps operated, almost independent of the location of the antennas within the array. It has the disadvantage that the Voyager signal is subjected to a 1.6 ms gap in signal reception per 52 ms control cycle, and to a 3-level quantization in the VLA processor. Analysis has shown the gap to be tolerable when the VLA is arrayed with Goldstone (Refs. 4, 5).

Two channels of the VLA signal transmission and processing equipment may be used: one with a 6 to 12 MHz IF bandwidth to carry the spacecraft data signal at roughly full precision, and a second (not shown in Fig. 5) with narrower bandwidth to be used to self-calibrate the VLA: i.e., to control the differential phase and delay in the system. Careful calibration or control of the differences between these two would be needed. Tests in 1983 had shown that it was feasible to self-calibrate the VLA on a natural signal source at a strength analogous to that of the Voyager spacecraft's signal in the narrow bandwidth (Ref. 6). More recent testing with the Voyager signal itself holds promise that the self-calibration can be achieved with the full bandwidth data channel (Ref. 7).

The baseline design X-band low-noise amplifier is a cryogenically cooled FET amplifier, similar to those in place at the VLA for its other frequency bands. The first two pre-prototype X-band LNAs are now in place on antennas at the VLA, mated with JPL-provided feedhorns, to enable testing of the X-band receive characteristics. A modern alternative to the FET, the so-called HEMT (high electron-mobility transistor), with the potential for a much reduced system temperature, will be evaluated for use in the LNAs (cf. NRAO Voyager Front-End Construction Plan, Rev. A, NRAO internal document, Feb. 15, 1985).

IV. Expected Level of VLA Support

The day of closest approach of the Voyager to the planet Neptune is August 24, 1989 (PDT). At that time, Voyager is visible daily from the VLA for an approximately eight hour "pass." That day, and the several days immediately surrounding it, are the times of greatest importance for the data to be gathered from the encounter. The time intervals for which arrayed support would be requested by the Voyager project include these critical passes plus several passes for testing the correctness of both configuration and operational procedures plus a number of additional passes both preceding and following the days of close encounter. Times not specifically requested, such as when Voyager is not visible, are presumed to be available for normal VLA astonomy purposes.

It is planned that the VLA will be made available for Voyager-directed support or operational testing for up to 40 observing intervals of up to 8-1/2 hours each. Operational verification tests will begin in April 1989, and continue into May. Actual spacecraft support could begin in mid July, about six weeks prior to encounter, and continue through four weeks after encounter. In addition to the spacecraft operations and operational testing, subsystem testing and verification would be required.

V. Organization Roles

The four organizations involved, NASA, NSF, JPL, and NRAO, will each play a part in preparing the VLA to support the Voyager at Neptune. As the principal beneficiary of this effort, NASA is providing the funding needed to support all of those changes to the VLA which are needed for Voyager. This includes work at both NRAO and JPL. The DSN organization will bear the primary responsibility for system design, planning, and management of the project. Implementation responsibility will be shared between NRAO and JPL. The mechanism implementing these roles is outlined in the "Management Plan for the VLA-GDSCC Telemetry Array Project" (D. W. Brown, JPL Document 1220-1, March 15, 1985 [internal document], Jet Propulsion Laboratory, Pasadena, CA).

With reference to Fig. 5, all equipment which is implemented into the VLA as an integral part of it, such as the X-band LNAs and down-converters, will be instrumented in a way that is suitable for general use by NRAO, and will be retained by NRAO-VLA upon completion of the Voyager support. All equipment which is adjoined to the VLA specfically for the Voyager support, and which is endemic to spacecraft data handling, such as the phase-locked receiver backend, specialized recording capability, satellite link to Goldstone, etc., will be de-implemented by JPL upon completion of Voyager support.

Again with reference to Fig. 5, NRAO will be responsible for the design and implementation of the X-band receiving equipment. This equipment is at least similar to if not identical to comparable elements already a part of the VLA for other frequency bands. The feeds have been designed by JPL for NRAO.

The equipment which is specific for spacecraft support, such as the phase-locked receiver and coherent detector, specialized recording, and communications to Goldstone, will be entirely the responsibility of the DSN, as will the overall operational coordination of the array. The interface between this equipment and the VLA instrumentation will be the single signal combined output of the VLA processor.

VI. Implementation Planning

Instrumentation of the VLA for Voyager support is a long and tedious task because of the large number of antennas involved. Rapid startup is essential if we are not to run afoul of manufacturing, installation, or checkout problems later. The current VLA implementation schedule is shown in Fig. 6. Target date for completion of all installation work is January 1989. The installation of the front-end assemblies throughout the 28 VLA antennas will be allotted two and a half years to provide an orderly process which does not conflict with other necessary VLA activities. Some of the mechanical work for mounting feeds, etc., will take four years because it must take place within the maintenance hangar, and was started at the beginning of 1985. The phase-locked receiver and other back-end elements are planned to be direct extensions of the implementation of the Parkes Radio Telescope for the Voyager encounter with Uranus (Ref. 2).

At a system level, there are tests scheduled in late 1984 and through 1985 which are essential to assuring that the desired capability is achievable. The initial single antenna tests, using a prototype LNA which was developed at the NRAO Charlottesville facility, together with a JPL "spare-parts" feed, have confirmed overall expectations of front end performance as well as provided the first opportunity to view the Voyager spacecraft signal through a part of the VLA's electronics. The dual antenna tests extend the signal path through the VLA correlator/combiner to the output port which would be in use in 1989, albeit with many fewer antennas involved in them. The early lab tests and analysis should support and help the interpretation of the testing at VLA.

A number of review decisions are embedded in the schedule. HEMTs are an improved technology for the FET amplifiers which show promise for significantly reducing their effective temperature, but require evaluation of reliability as well as performance. Back-up power, if deemed necessary, and real-time link equipment would be leased commercial equipment, each requiring appropriate lead time for ordering, contracting, and installation.

VII. Other Users

Other missions and other ground-based radio science users were explored for possible joint interest in a VLA configured so it was capable of 8.4 GHz signal reception. One existing mission, ICE, the International Cometary Explorer, is an S-band mission, and its critical need for large aperture support is occurring in September 1985, long before such capabilities could be available. Of the future mission options examined during the study, most are at modest data rates, and only one, a Titan Probe (1996), showed any benefit from the type of ground aperture increase available through the VLA. Even this benefit seemed minor, and it was concluded that the arrangements with the VLA for Voyager support should be considered as unique to the Voyager, over the next dozen years or so.

There is however additional ground-based science which becomes possible with the X-band capability added to the VLA. The extra frequency, for example, is of some interest in monitoring the spectrum of variable stars and novae, and possibly for Faraday rotation effects in polarization studies. However, there are no spectral lines of more than modest interest within the band, and the planned capability provides no increased sensitivity for detection of continuum sources (A. R. Thompson, NRAO-VLA, private communication, April 23, 1984).

There is some significant interest in the VLA X-band capability for planetary radar, with the DSN Goldstone 64-meter site as transmitter and the VLA as receiver. One instance of this is topographic mapping of the nearer planets such as Venus and Mars. With existing radars such mapping is done by a delay-doppler technique which depends upon some assumptions concerning the general form of the target. The resolution of the VLA would allow these assumptions to be relaxed, thus providing a more direct measurement of the surface shape. Radar observations of more distant targets such as the outer planet satellites and rings would capitalize upon the greater sensitivity of the VLA. Observing proposals for planetary radar observations will be input to the regular VLA proposal evaluation process.

Observations for VLBI at the DSN frequencies for astronomy or other applications could also be of interest. The X-band on the VLA will provide another band in common with the planned Very Long Baseline Array (Ref. 8), which would be useful, though not sufficient by itself to cause it to be implemented.

Acknowledgment

The concept described here for VLA support to the Voyager at Neptune owes a great deal to the support received from the staff at NRAO, and from many members of the JPL Telecommunications Engineering and Voyager Project organizations. Noteworthy here are Dr. A. R. Thompson, Dr. P. Napier, and Dr. S. Weinreb of NRAO, and C. E. Kohlhase, D. A. Bathker, R. C. Clauss, Dr. S. J. Kerridge and B. D. Madsen of JPL.

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Table 1. Voyager Uranus and Neptune data rates

Data Rate, kb/s	Data Type	Equivalent Full Images/hr
29.9	Full frame imaging	13
21.6	Compressed imaging and playback	13 + 6
19.2	Half frame imaging	6
14.4	Compressed imaging	13
11.2	Compressed imaging	9
8.4	Compressed imaging	5
7.2	General science and engineering	None

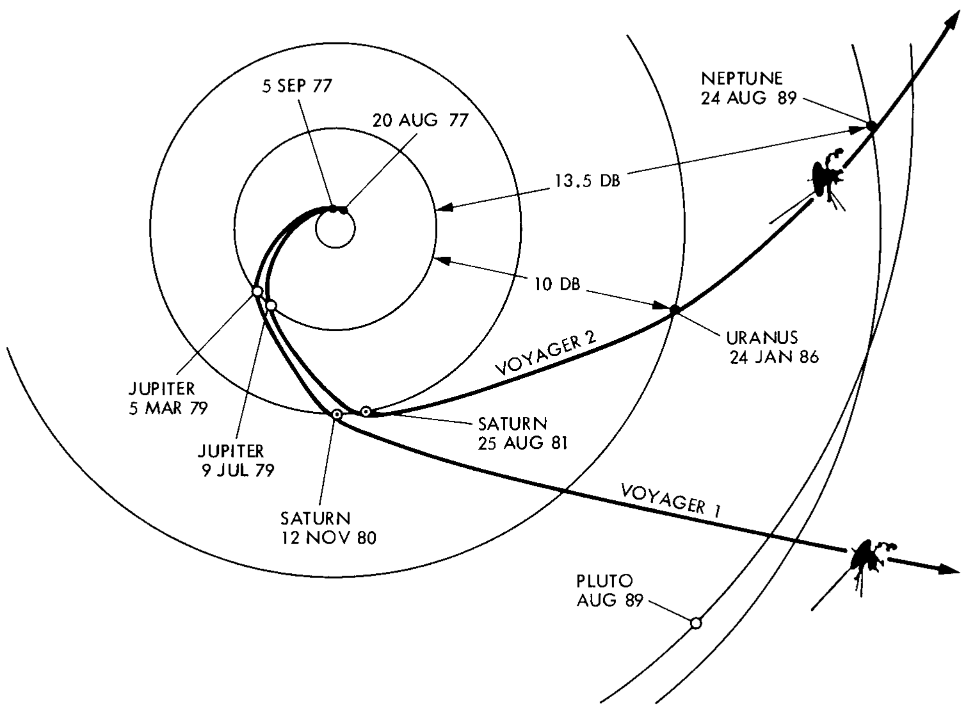


Fig. 1. Voyager trajectory

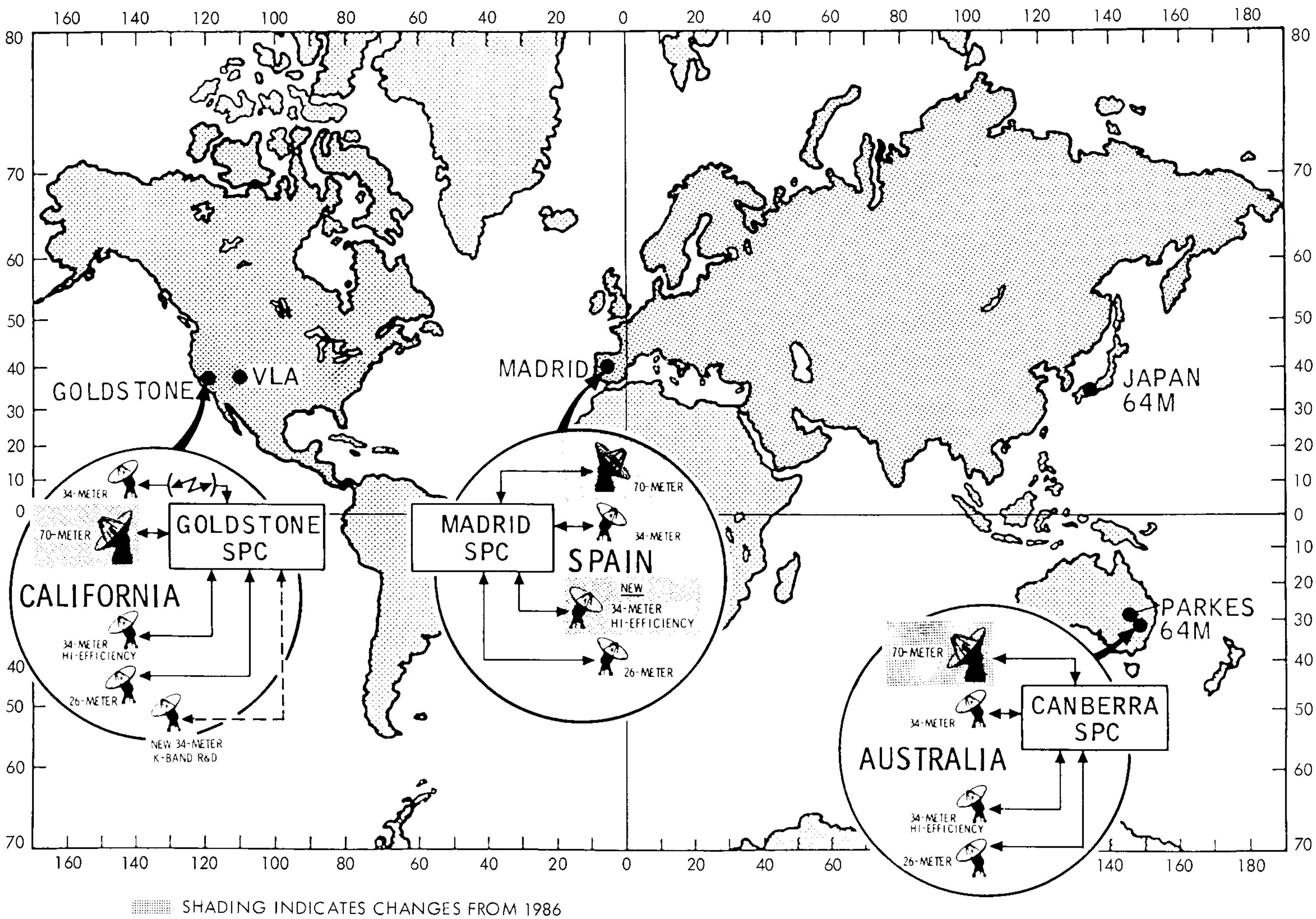


Fig. 2. 1989 network configuration and candidate facilities

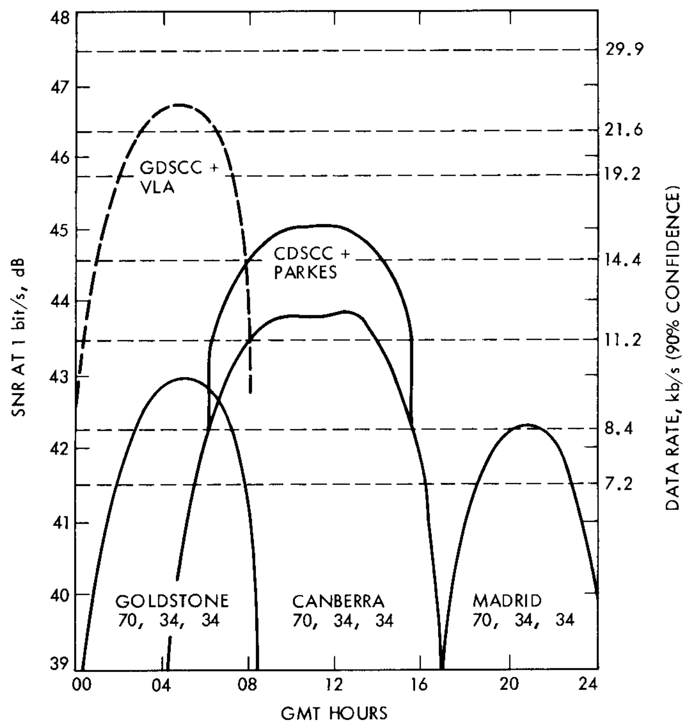


Fig. 3. Telecommunications at Neptune

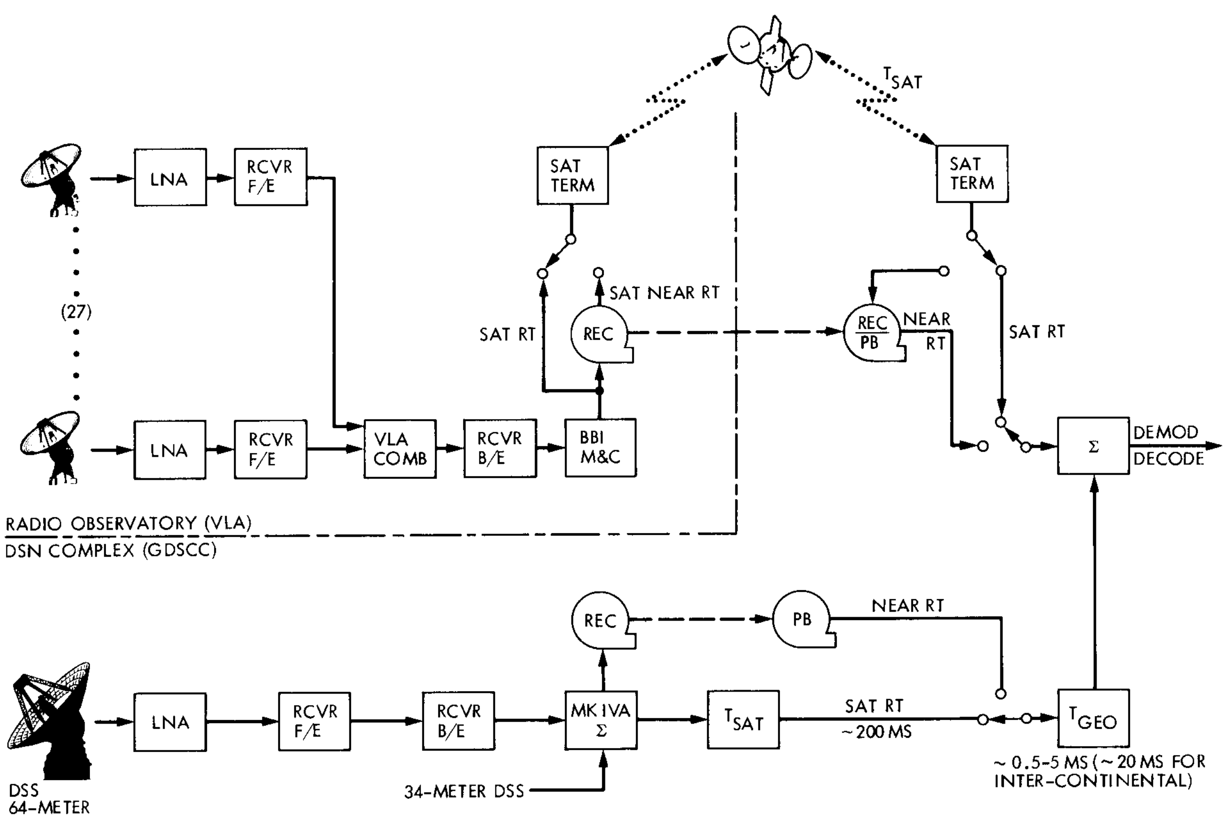


Fig. 4. Arraying functional block diagram

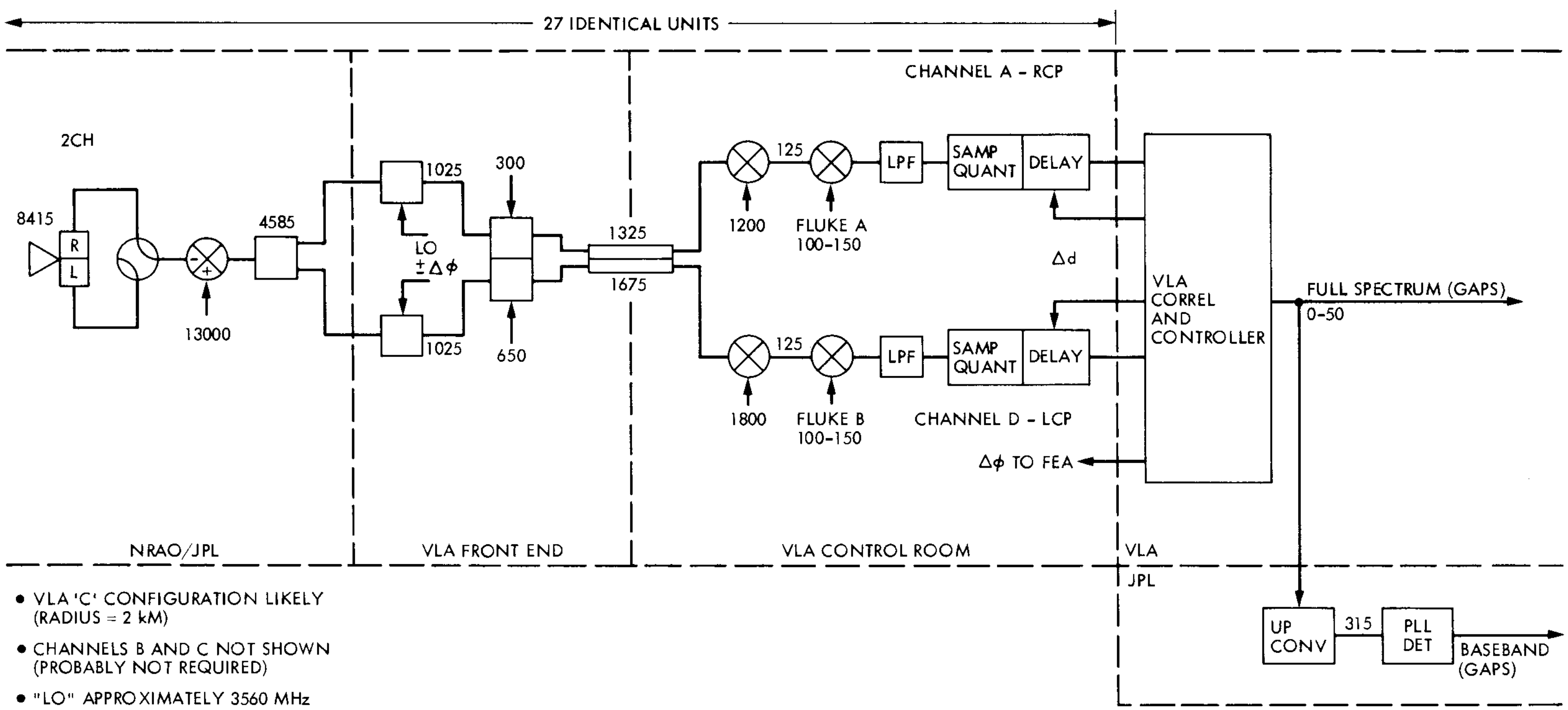
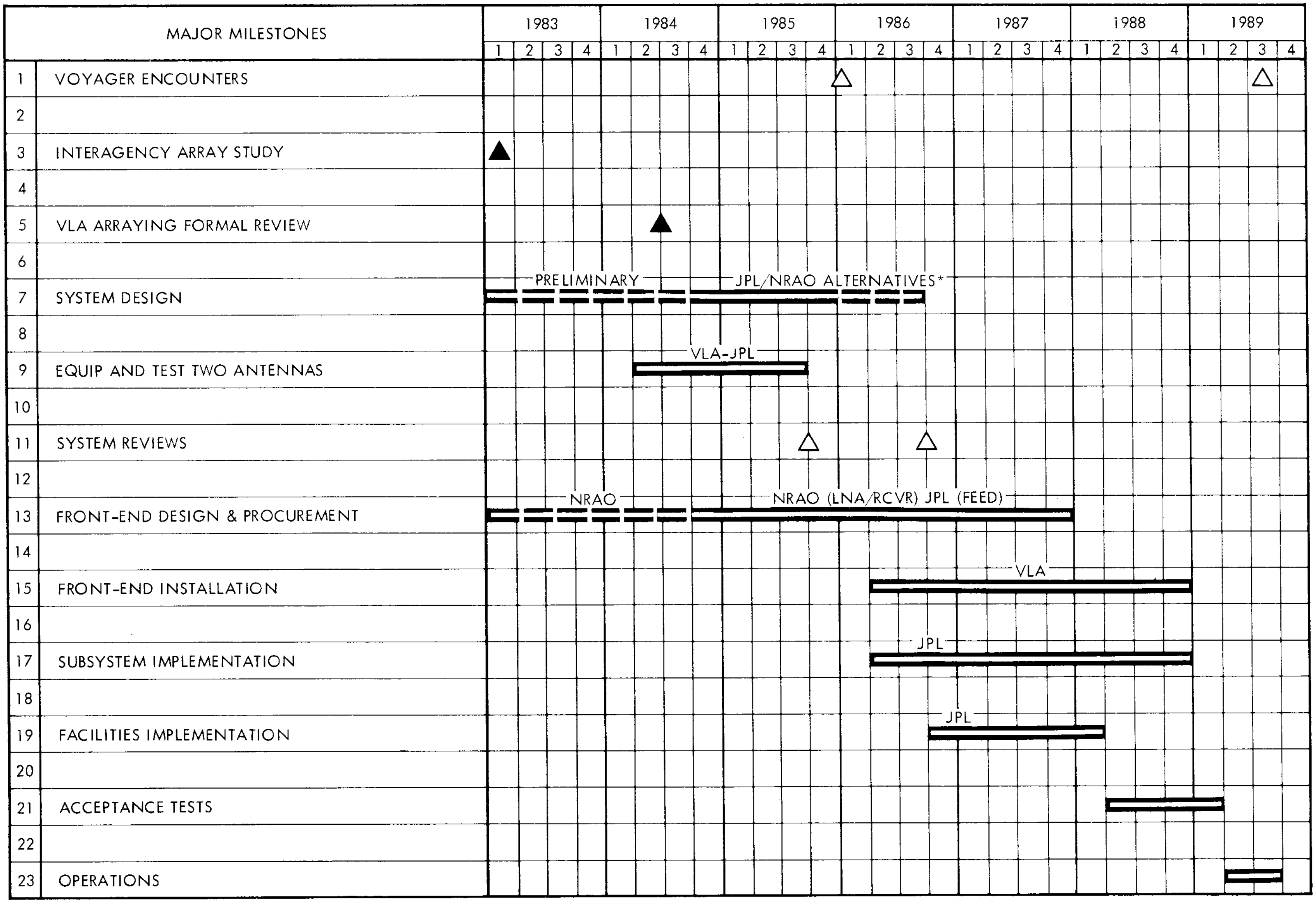


Fig. 5. VLA block diagram



* HEMT VS FET, AUXILIARY POWER, URANUS RECORDING EXPERIENCE

Fig. 6. VLA-GDSCC Telemetry Array project schedule